Design and Construction of Electronic Aid for Visually Impaired People

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***Abstract*—The NavGuide is a novel electronic device to assist visually impaired people with obstacle free path-finding. The highlight of the NavGuide system is that it provides simplified information on the surrounding environment and deduces priority information without causing information overload. The priority information is provided to the user through vibration and audio feedback mechanisms. The proof-of-concept device consists of a low power embedded system with ultrasonic sensors, vibration motors, and a battery. To test the effectiveness of the NavGuide system in daily-life mobility of visually impaired people, we performed an evaluation using 70 blind people of the "school & home for the blind." All evaluations were performed in controlled, real-world test environments with the NavGuide and traditional white cane. The evaluation results show that NavGuide is a useful aid in the detection of obstacles, wet floors, and ascending staircases and its performance is better than that of a white cane.**

***Index Terms*—Assistive technology, blind people, electronic navigation aid, man machine systems, navigation, obstacle detection, rehabilitation, visually impaired people, wearable system.**

I. Introduction

VISION plays a vital role in gaining knowledge of the surrounding world. However, loss of vision makes it difficult to live a normal daily life. According to the World Health Organization, there are 285 million people in the world with visual impairment, 39 million of whom are blind, and 246 million with low vision. About 90% of the world's visually impaired people live in low-income settings [14]. The number of blind people has been projected to double by 2020. Traditionally, a white cane is used as a walking aid by visually impaired people. White canes are inexpensive, lightweight, and can detect obstacles on the ground. However, a white cane suffers from the following three fundamental shortcomings.

1) It requires the user's constant activity and conscious efforts to actively scan the surrounding environment.
2) The stick can only detect obstacles up to knee-level. Hence, the user cannot detect raised obstacles, such as scaffoldings and portable ladders. This poses a collision danger.
3) The stick can only detect obstacles which are at a distance of 1 m from the user, giving little time to take any preventive actions.

Guide dogs may also assist visually impaired persons to avoid obstacles in their travel path. However, guide dogs require training and fully trained guide dogs are very costly. In addition, it is a challenging task for a visually impaired person to care appropriately for another living thing. Furthermore, special training is required for visually impaired people to handle and take care of guide dogs, which is difficult and costly.

As per the estimates of guiding eyes for the blind, only 10 000 guide dog teams are currently working in the U.S., whereas the total number of visually disabled people in the U.S. is 7 327 800 [13], [15]. Similar to white cane, a guide dog provides short range obstacle detection and fails to detect head level obstacles.

To improve mobility and speed of a person with visual impairments, several researchers introduced electronic travel aids (ETAs). These ETAs are available in different forms, such as handheld devices, smart canes, and wearable systems. However, acceptance of available ETAs is quite low among visually impaired people [4]. This does not imply that visually impaired people are resistive to technological aids; rather it asserts the requirement of further research to improve on the usability and acceptability of ETAs [5]. Safe and independent mobility is still a challenge for visually impaired people.

As per the guidelines of the National Research Council, the ETAs for visually impaired people should assist in detecting floor-level as well as head-level obstacles to achieve safe mobility and understanding travel surface information. These aids should have minimum interface with the natural sensory channels [12]. The majority of ETA systems have adopted some of these guidelines. In the following paragraphs, we present a brief overview of some existing ETAs.

The NavBelt [31], is based on mobile robotics technologies to assist visually impaired people. It is a portable device equipped with ultrasonic sensors and a computer. However, it requires conscious efforts form the user to comprehend its audio cues. GuideCane [32], K-Sonar Cane [17], Ultracane [33], and EMC [4] are electronic travel aid canes that use ultrasonic sensors. GuideCane is a robotic guiding cane that can detect only floor level front-way and sideways obstacles. This cane is large in size and has limited scanning area [12]. K-Sonar Cane uses

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variable frequency sound patterns to convey the distance of obstacles. It requires considerable conscious effort from the user to overcome its audio cues. Ultracane detects floor and head level obstacles. The electronic mobility cane (EMC) detects floor-level and knee-level obstacles. However, the system should be held straight upright by its users and diagonal or slanted usage of EMC reduces detection of obstacles in the front. Other systems such as CyARM [19], the sonic torch [21], and kaspa system [7], [8] are handheld obstacle detection systems based on echolocation. These systems require a user to actively scan the environment to detect obstacles by continuously moving his/her hand in many directions.

Poor user interface, functional complexity, heavy weight, large size, and high cost are some of the issues responsible for low acceptability of existing ETAs. Inadequate communication between ETA developers and potential users may also be a reason for this low acceptability. Therefore, we conducted a survey in the *School & Home for the Blind* to understand users requirements and expectations from an electronic travel navigation system. We interacted with 177 visually impaired people and their care takers. We asked the same set of questions to all participants. Of the interviewed participants 95.48% acknowledged inadequate information on the surrounding environment provided by a white cane. They also acknowledged lack of adequate information about the nature of the floor provided by a white cane. Close to 88% of the participants reported that conscious efforts and active scanning of the environment are required while using a white cane. A total of 71.18% of the participants reported slipping accidents caused by wet floors. In all, 90.30% of the visually impaired users preferred a portable and lightweight electronic aid system for attending to their mobility needs, such as floor-level and head-level obstacle detection and wet floor detection. In addition, close to 24% of the participants requested for a cost effective system (less than $20 USD).

To address the limitations of existing ETA systems, we designed and developed the NavGuide, an electronic travel aid that detects wet floors, floor-level obstacles, and knee-level obstacles. The NavGuide system categorizes obstacles and surrounding environment situations and provides priority information to its users. In addition, the NavGuide assists visually impaired people in left turn, right turn, blocked front-way, and wet floor situations. The NavGuide provides simplified and prioritized information of the surrounding environment to its user through tactile (vibration) and auditory senses based feedback mechanisms. This paper covers design, construction, and evaluation of the NavGuide.

The rest of this paper is organized as follows: First, Section II analyzes related work to identify challenges in detecting obstacles and providing safe mobility to visually impaired people. Section III describes design of the solution and Section IV explains implementation and experimentation details. Further, Section V presents results of the proposed solution. Section VI demonstrates performance of the proposed solution using statistical analysis. Section VII examines possible limitations and suggests ways for improvement. Finally, Section VIII concludes the paper.

II. Literature Analysis

ETAs use different technologies, such as lasers, ultrasonic sensors, and digital cameras to gather information on the surrounding environment. We have categorized ETAs in two categories based on their approach to obstacle detection namely active methods and passive methods. Active obstacle detection methods use range detection technologies, such as laser scanners, structured light, or ultrasound to detect the presence of an obstacle in the surrounding, whereas passive methods detect obstacles using passive measurements in images or videos. The fundamental difference between range-based and camera-based obstacle detection systems is the obstacle detection criterion. In range-based systems, obstacles are objects that extend a minimum distance above the ground. In camera-based systems, obstacles are objects that differ in appearance from the ground surface.

The feedback mechanisms used by the ETAs are audio, tactile, or both. The advantage of tactile feedback is that it does not block the auditory sense. Many studies have proposed solutions to assist visually impaired people. Some of these studies from the last three decades and lists of their limitations in fulfilling the requirements of visually impaired people are summarized below.

A. Active Methods

Echolocation, 1991 [18] used audio to provide feedback to users. Two ultrasonic sensors are used on conventional eyeglasses and audio feedback is provided to users via headphones. It is portable and detects head-level obstacles. However, it fails to detect floor-level obstacles and wet floors. vOICe, 1992 [25] used audio to provide feedback to users on detected obstacles. A digital camera is attached to conventional eyeglasses and audio feedback is provided to users via headphones. It requires extensive training for users due to complicated sound patterns. In addition, it does not detect wet floors and floor-level obstacles.

NavBelt, 1998 [31] uses audio to provide feedback to users. It uses ultrasonic sensors and applies a mobile robot obstacle avoidance technique. However, it is large in size and its prototype is heavy. In additon, conscious efforts from the user are required to comprehend its audio cues and it does not detect wet floors and floor-level obstacles. GuideCane, 2001 [32] used tactile feedback to notify users about detected obstacles. It does not require active scanning of the surrounding area by users. However, it has a limited scanning area. It is large in size and excludes the user from taking navigation decisions.

CyARM, 2005 [19] uses tactile feedback to notify users about the detected obstacles. It is a handled device weighting 500 gm. It uses ultrasonic sensors to detect obstacles and calculates distances of obstacles from the user. However, it requires active scanning of the environment by continuous movement of the hand in multidirection. In addition, it does not detect wet floors. NAVI, 2007 [30] uses audio to provide feedback to users. It uses a digital video camera to detect obstacles in the front and stereo headphones to provide audio feedback to users. However, it is bulky and does not detect wet floors.

K-Sonar Cane, 2008 [17] uses audio to provide feedback to users on detected obstacles. It embeds ultrasonic sensors in a

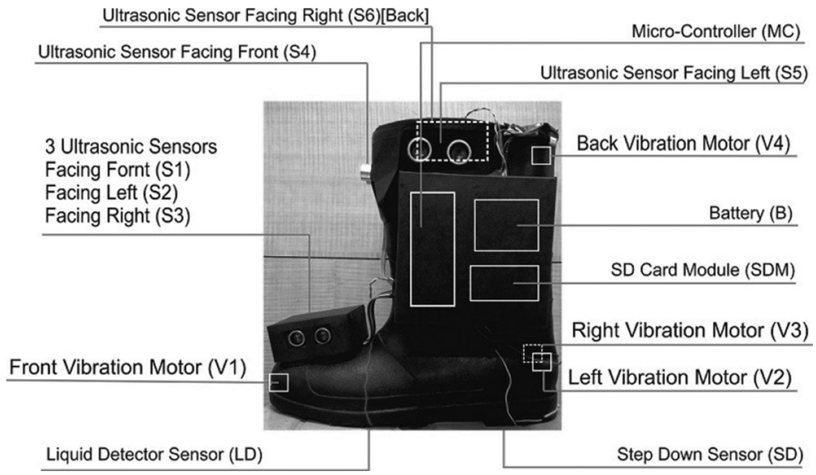

Fig. 1. Assembled NavGuide Shoe showing the placement of system components.

white cane and converts distances into audio feedback. It uses variable frequency sound patterns to convey the distance of obstacles. However, conscious efforts from the user are required to comprehend its audio cues. Moreover, it does not detect wet floors and head-level obstacles. Ultracane, 2012 [33] uses tactile feedback to notify users about detected obstacles. It uses embedded laser scanners in a white cane. A vibration button on ultracane warns the user of potential obstacles in the path. However, it does not detect head-level obstacles and wet floors.

Ando *et al.* [3] and EMC, 2014 [4] use both tactile and audio feedbacks to notify users about detected obstacles. It embeds ultrasonic sensors in a white cane and provides the user with both tactile and audio feedbacks. It detects floor-level and knee-level obstacles. However, diagonal or slanted usage of EMC reduces detection of obstacles in the front.

Miniguide [16] used both tactile and audio feedbacks to notify users about detected obstacles. It is a handheld device. It uses variation in vibration rate to indicate the distance of an object. It also provides audio feedback using earphones. However, it is costly (approx. $300). Moreover, it does not detect wet floors. Mini-Radar [10] uses audio to provide feedback to users. It uses sonar to detect obstacles in the front. It provides audio feedback to the user when obstacles are detected. However, it is a costly device. It does not detect wet floors.

LaserCane [22] uses both tactile and audio feedbacks to notify users about detected obstacles. It is a white cane equipped with three laser sensors. It uses vibration and audio to provide warning when an obstacle is detected. However, it is very costly. It does not detect wet floors. Moreover, conscious efforts from the user are required to scan the surrounding area. Furthermore, it cannot detect transparent glass as laser beams travel through it instead of reflecting back to the origin.

B. Passive Methods

Several research efforts [1], [6], [20], [26], [34], [37], [41] used a camera to detect obstacles in real-time targeted at aiding the blind and low-vision people. Vision-based systems provide rich information about the environment and aid in reliable detection of obstacles. However, video processing tasks consume a considerable amount of energy and require high processing power and memory to provide real-time responses. Ye *et al.* [38] proposed a robotic navigation aid called a co-robotic cane (CRC). In an indoor environment for both pose estimation and object recognition, the CRC uses a three-dimensional (3-D) camera. In active mode, it guides the user by steering itself into the desired direction of travel, while in the passive mode it functions as a white cane with enhanced computer-vision. The disadvantage of most camera based solutions is their limited field of view.

Lee *et al.* [23] uses geomagnetic field effects to help visually impaired persons navigate indoor and outdoor. To help the user follow a map, magnetic information indicating special locations incorporated as waypoints on a map. Surrounding obstacle information is vital for visually impaired people if they are to avoid obstacles and hazards while walking around. In [2], the authors designed haptic direction indicators to provide directional information in real time through kinesthetic cues. Other research efforts [27], [28] performed analysis of challenges to learn to perform touchscreen gestures by visually impaired people and on–body interaction, in which the user employs his/her own body as an input surface.

Recent research efforts [9], [29], [35], [36], [39], [40] focused on video analysis and compression techniques for faster multi-core processing as well as object detection in very high resolution optical remote sensing images. These techniques provide improvements on video encoding and processing speedup of videos. Moreover, these methods cannot only detect obstacles, but also perform object recognition. Despite the progress made in object detection using images, it is problematic using cameras to detect obstacles for visually impaired people because video processing consumes a lot of energy due to high computation requirements.

III. DESIGN OF THE NAVGUIDE

This section describes the design and structure of the NavGuide, electronic device to assist visually impaired people in obstacle free path-finding. Fig. 1 shows an overview of the NavGuide obstacle detection and navigation assistance system

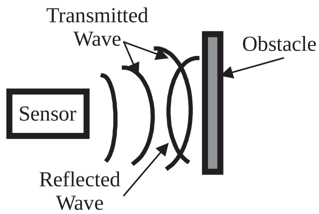

Fig. 2. Obstacle detection based on Reflection of sound wave emitted by an ultrasonic sensor.

for visually impaired people. The main goal of the NavGuide is to create a logical map of the surrounding and provide appropriate feedback to the user about the obstacles in the surrounding. The NavGuide consists of six ultrasonic sensors, a wet floor detector sensor, a step down button, microcontroller circuits, four vibration motors, and a battery for power supply. An ultrasonic sensor is used to send out high frequency sound waves and record the time it takes for the reflected sound waves to return. The total of six ultrasonic sensors are divided in two groups, i.e., group 1 and group 2. Group 1 sensors (S1, S2, S3) detect floor level obstacles while group 2 sensors (S4, S5, S6) detect knee level obstacles. Sensors S1 and S4 are front facing, S2 and S5 are left facing and S3 and S6 face towards the right side. All six ultrasonic sensors are wide beam ping sensors. An ultrasonic sensor uses high frequency sound waves to find the distance of an object from the NavGuide. When a sound wave hits an object, it is reflected off the object as shown in Fig. 2. An object may be directly in the front of the transmitter or at an angle for the signal to be reflected and received by the ultrasonic sensor.

A. Functionality of the NavGuide

1) Generates a logical map of the surrounding, for detecting the obstacles in front, on the left, and on the right side of NavGuide.
2) Obstacles from floor-level upto knee-level are detected by NavGuide.
3) Wet Floors are detected if stepped on by a visually impaired person using NavGuide.
4) Tactile feedback is provided to the user of NavGuide through vibration motors.
5) Auditory feedback is provided by the Navguide to its user using wired or wireless headphones.

A total of four vibration motors are used in the system. One vibration motor (V1) attached to left-side of a shoe which vibrates on detection of an obstacle on the left side of NavGuide, a second V2 attached to right side of a shoe which vibrates on detection of an obstacle on right side of NavGuide, a third V3 is attached to the front side of a shoe which vibrates on detection of an obstacle in front of NavGuide, and a fourth V4 is attached to the back side of the shoe which vibrates on detection of wet floor under NavGuide as shown in Fig. 1. A microcontroller circuit for processing the inputs from sensors and managing tactile and auditory outputs, a wet floor detection sensor, a step down button to detect the down-state of the foot and a power supply for providing power to all equipment fitted and connected to the shoe as shown in Fig 1.

TABLE I
DISTANCE OF ULTRASONIC SENSORS FROM SURFACE AND THEIR SENSING DIRECTION W.R.T CONSUMER

Ultrasonic Sensor ID	Distance from Surface (cm)	Sensing Direction
S1	6	Front
S2	6	Left
S3	6	Right
S4	25	Front
S5	26	Left
S6	26	Right

TABLE II
WIDTH AND HEIGHT DIFFERENCE BETWEEN FRONT DIRECTION SENSORS S1 AND S4 POSITIONS IN NAVGUIDE

Size of Shoes (UK)	Size (cm)	Width Difference (δ) (cm)	Height Difference (γ) (cm)
7	24.4	8.7	15.2
8	25.4	9.1	16.1
9	26	9.5	18
10	27	10	18.8
11	27.9	10.6	19.9

Table I shows distances of embeded ultrasonic sensors from the surface and their sensing direction with respect to the direction faced by the shoes. We assumed that the user of NavGuide has put his foot straight w.r.t to the direction faced by the user. The diagonal or slanted usage of the NavGuide changes the angle of its ultrasonic sensors beam with the object, hence reduces its obstacle detection accuracy. An angle of 20° to 30° in usage of NavGuide provides faithful results for detections of obstacles.

Table II shows the width and height differences between front direction sensors S1 and S4 placement in NavGuide depending on various standard sizes of shoes according to the United Kingdom standards.

A microcontroller controls the ultrasonic sensors to emit a short ultrasonic burst for inferring the logical map of the surrounding objects and obstacles. The distance of an object is calculated using the following equation

$$\text{Distance travelled (D)} = \text{speed of sound} \times \text{ time elapsed.} \tag{1}$$

In dry air, the speed of sound is 343.2 m/s and the distance between the sensor and the object is one-half the distance traveled by the sound wave. Hence, the distance (1) becomes

$$D = (343.2\ \mathrm{m/s}) \times \Delta t \times 0.5. \tag{2}$$

The NavGuide shoes provide feedback through audio and tactile outputs. The audio samples to be played are stored in a micro secure digital (SD) card inserted in an SD card module connected with the microcontroller. The audio feedback is provided through mono wireless headphones to the user. By analyzing the logical map instance of the surrounding for the presence of any obstacles, appropriate voice messages are played.

B. Constructing Logical Map of the Surrounding Environment

The six ultrasonic sensors placed on the NavGuide shoe continuously sense the obstacles in their respective scopes along with a wet floor detector sensor sensing wet floor if stepped upon by the NavGuide shoe. The obstacle data from each ultrasonic sensor and wet floor data from the wet floor detector sensor is collected by the microcontroller. Using this data, a logical map containing the position of each obstacle in front, on the left and, on the right side of the NavGuide shoe is created. The wet floor status is also added in the logical map data. Using auditory and tactile feedback mechanisms the user of the NavGuide is notified about the obstacles in the surrounding. This logical map data is continuously updated at each foot step.

1) Ascending Staircase Detection: According to the international residential code (IRC) for staircase, dimensions, tread depth, and riser height are 25 and 19.6 cm, respectively [11]. The part of the staircase that is stepped on is called tread depth and vertical portion between two treads on the stair is called riser height. To detect an ascending staircase, the *x*-coordinate value of an obstacle is measured for all three ultrasonic sensors. The *x*-coordinate value of an obstacle is calculated by using the distance measured using the following equation

$$x_{\text{coordinate}} = \cos\theta \times D_i. \tag{3}$$

Here, D_i is distance calculated using (2) by ith ultrasonic sensor (i = 1,2,...,6) and θ is angle of the sensor with the horizontal. The value of θ for all sensors is 0° if the leg of the user is in a vertical position.

Suppose, $S1_x$ represents the *x*-coordinate value calculated by an ultrasonic sensor S1. Similarly, $S4_x$ represents the *x*-coordinate value calculated by an ultrasonic sensor S4 and $S2_x$ represents the *x*-coordinate value calculated by an ultrasonic sensor S2. The presence of the ascending staircase in the front is detected if conditions in (4) is fulfilled. The values of δ and γ are given in the Table II. Similarly, (5) and (6) detect presence of the ascending staircase in the left and right direction of the user, respectively,

$$[((S1_x < S4_x)\&\&((S4_x - (S1_x + \delta)) \geq T_d))] \tag{4}$$

$$[((S2_x < S5_x)\&\&((S5_x - (S2_x + \delta)) \geq T_d))] \tag{5}$$

$$[((S3_x < S6_x)\&\&((S6_x - (S3_x + \delta)) \geq T_d))]. \tag{6}$$

Here, T_d is the value of the tread depth which is 25 cm and R_h is the value of the riser height which is 19.6 cm according to the IRC. A limitation of NavGuide is that an obstacle with backward slanting shape in the front that satisfies the conditions in (4) is detected by NavGuide as an ascending staircase.

2) Floor-Level Obstacle Detection: An obstacle that is detected by group1 ultrasonic sensors (S1, S2, S3) is considered as a floor-level obstacle. The presence of a floor level obstacle infront is detected by the S1 sensor. The S2 sensor detects floor level obstacles in the left direction if the shoes are considered to be facing forward. Similarly, the S3 sensor detects floor level obstacles on the right.

3) Knee-Level Obstacle Detection: An obstacle that is detected by both ultrasonic sensors S1 and S4 is considered as knee-level obstacle. The presence of a knee-level obstacle in the front is confirmed if condition in (7) is satisfied

$$[(S1_x < S4_x)\&\&((S4_x - S1_x) \leq \delta)] \tag{7}$$

$$[(S2_x < S5_x)\&\&((S5_x - S2_x) \leq \delta)] \tag{8}$$

$$[(S3_x < S6_x)\&\&((S6_x - S3_x) \leq \delta)]. \tag{9}$$

Here, δ is the width difference between S1 and S4 according to the Table II. Similarly, (8) and (9) detect the presence of a knee-level obstacle in the left and right direction of the user, respectively.

4) Knee-Level Forward Slanting Obstacle Detection: The presence of a knee-level forward slanting obstacle in the front is confirmed if condition in (10) is satisfied. Similarly, (11) and (12) detect the presence of a knee-level forward slanting obstacle in the left and right direction of the user, respectively

$$[S4_x < (S1_x + \delta)] \tag{10}$$

$$[S5_x < (S2_x + \delta)] \tag{11}$$

$$[S6_x < (S3_x + \delta)]. \tag{12}$$

5) Wet-Floor Detection: The wet floor detector sensor mounted beneath of the shoe detects any liquid which is spilled on the floor on which the user steps.

IV. Implementation and Experiments

A. Implementation

The NavGuide system consists of three modules namely, Data gathering module (DGM), logical map construction module (LMCM), and feedback module (FBM).

1) DGM: This module includes ultrasonic sensors and wet floor detectors to collect data from the surrounding and to send the acquired information to the LMCM module.
2) LMCM: This module uses a customized microcontroller circuit for processing the input received from the DGM and constructs a logical map of the surrounding. The logical map consists of data about the obstacles on the front side, the left side, and the right side of the NavGuide shoe along with the wet floor status below. This module infers priority information based on the current position and direction of movement of the user. The LMCM sends inferred priority information to the feedback module.
3) FBM: The role of the FBM is to provide feedback to the consumer in form of tactile and auditory stimulation. This module includes an SD card module and an audio decoder module. Using the priority information received from the LMCM module, it provides appropriate feedback to the user. The audio feedback is provided by playing the appropriate voice file from the SD card. Tactile Feedback is provided using vibrator motors. There are a total of four vibrator motors of 11000 rpm with each fitted on the

TABLE III
DETAILS ABOUT PARTICIPANTS

Gender	Total Blind	Low Vision
Male	28	13
Female	20	9
Total	48	22

TABLE IV
AUDIO FEEDBACK PROVIDED TO CONSUMERS IN VARIOUS SITUATIONS BY NAVGUIDE

Sr.No.	Situation	Audio Feedback
1	Obstacle in front	Blocked front
2	Obstacle on left	Blocked left
3	Obstacle on right	Blocked right
4	Obstacle on left and front sides	Go right
5	Obstacle on right and front sides	Go left
6	Obstacle on left and right sides	Go straight
7	Obstacle on left, right and front sides	All blocked
8	Staircase detected	Stairs ahead
9	Wet floor detected	Wet floor

internal surface of the shoe towards the left, right, front, and back.

B. Experiments

For testing the usability and performance of NavGuide, a study was conducted in which 70 visually imhose 70 participants, 48 were totally blind of which 28 were male and 20 were female. The remaining 22 participants had low vision of which 13 were male and 9 were female as shown in Table III. The participants were white cane users who had good command over using it.

A short training of 9 h was conducted over a period of three days for the participants during which they were taught how to use NavGuide and its tactile and audio feedbacks. The participants learnt about the location of the vibrator motors, and their behavior in various cases of obstacles in the surrounding along with the different voices played as audio feedback as listed in Table IV.

After the training, four experiments were conducted in controlled environments. To test the accuracy of the logical map constructed by NavGuide and feedback provided to the users, artificial obstacles of varying sizes were created using carton boxes and bricks. The first experiment was conducted in a controlled indoor environment where ten obstacles were arranged within a rectangular surface area of 240 cm $\times$ 340 cm as shown in Fig. 3. The task for the participants was to start from one side of the rectangle and reach the opposite side crossing all the obstacles in their path.

The second experiment was conducted in a controlled outdoor environment where 30 obstacles were arranged on a cement-concrete road which was 410 cm wide and 3000 cm in length. The participants started from one side, walked over the length of the road and reached the opposite end, crossing the obstacles in their path.

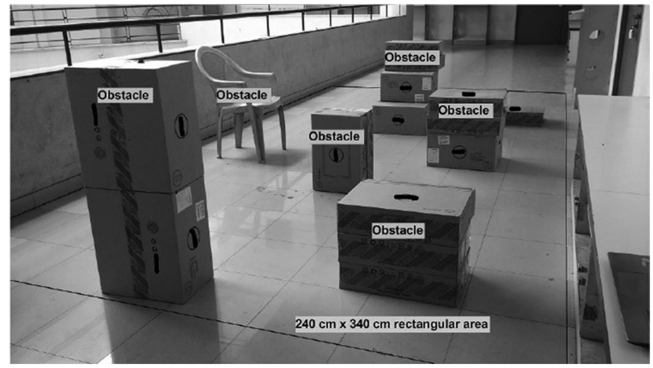

Fig. 3. Experimental setup for indoor environment with obstacles at random places.

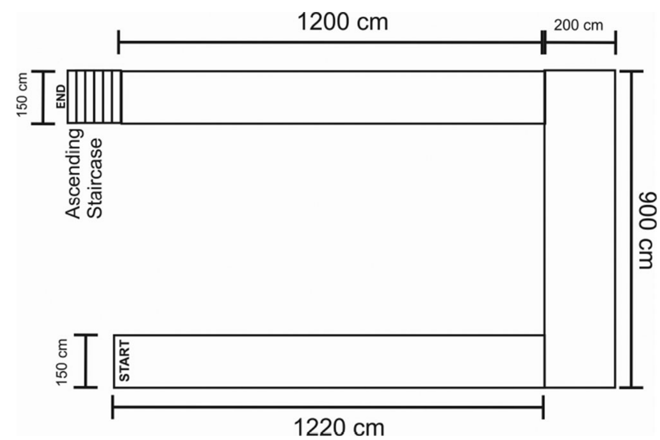

Fig. 4. "U"-shaped corridor with staircase at the end.

The third experiment was conducted in a controlled U-shaped corridor with one end having an ascending staircase as shown in Fig. 4. For measuring the area, the corridor was divided into three rectangles of dimensions 1220 cm $\times$ 150 cm, 900 cm $\times$ 200 cm, and 1200 cm $\times$ 150 cm. The staircase had six steps, each step had thread depth of 25 cm, width of 150 cm and raiser height of 20 cm. The participants walked from point A to point B, crossing the obstacles and climbing the staircase.

In the fourth experiment, a 1000 cm $\times$ 1000 cm rectangular room was divided into 50 blocks. Water was spilled in 30 randomly selected blocks. Each participant was asked to walk in the room and identify the blocks where floor is wet.

In the first three experiments, participants were asked to participate two times, the first time using white cane and the second time wearing the NavGuide. The performance measures were the total number of obstacles the participant collided with, the total time taken to complete one experiment and the average walking speed per experiment were closely observed and recorded for each participant. The fourth experiment was performed once by each participant with NavGuide, where each time the participant detected a wet floor situation, one point was awarded to the participant, and noting the total score of each participant.

TABLE V
AVERAGE NUMBER OF OBSTACLES COLLIDED (MAXIMUM 10 OBSTACLES: 5 FLOOR-LEVEL, 5 KNEE-LEVEL) IN EXPERIMENT ONE

Blindness Type	Gender	White Cane			NavGuide		
		Floor level	Knee level	Total	Floor level	Knee level	Total
Total Blind	Male	2.56	1.86	4.42	0.88	0.94	1.82
	Female	2.43	1.73	4.16	1.05	0.95	2.00
Low Vision	Male	1.62	0.83	2.45	0.75	0.63	1.38
	Female	1.56	0.78	2.34	0.57	0.51	1.08

TABLE VI
AVERAGE NUMBER OF OBSTACLES COLLIDED (MAXIMUM 30 OBSTACLES: 15 FLOOR-LEVEL, 15 KNEE-LEVEL) IN THE EXPERIMENT TWO

Blindness Type	Gender	White Cane			NavGuide		
		Floor level	Knee level	Total	Floor level	Knee level	Total
Total Blind	Male	4.62	2.71	7.33	2.69	2.24	4.93
	Female	4.29	2.92	7.21	2.67	1.73	4.40
Low Vision	Male	2.68	1.68	4.36	1.26	1.31	2.57
	Female	1.85	1.54	3.39	0.78	0.79	1.57

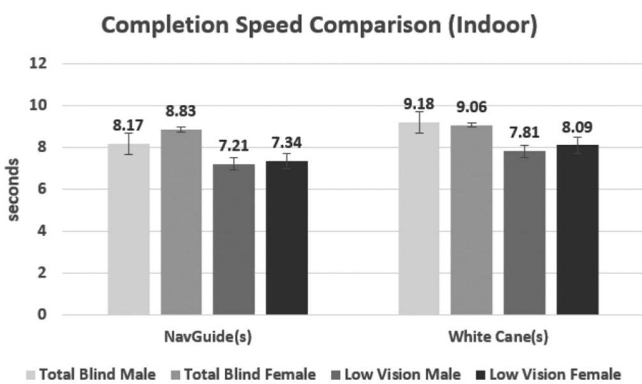

Fig. 5. Average completion speed of experiment one by participants.

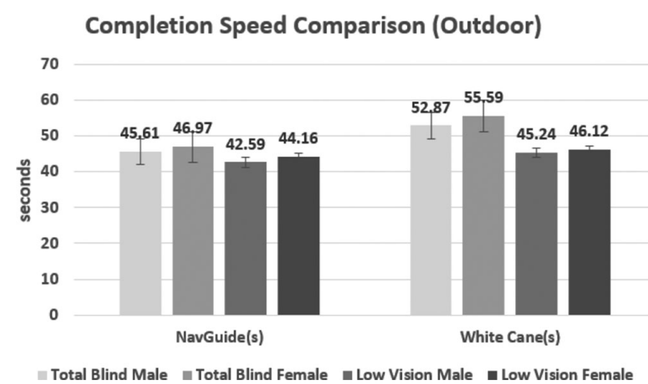

Fig. 6. Average completion speed of second experiment by participants.

V. RESULTS

A total of 70 users provided oral consent and participated in the controlled test environments. Each participant participated in four experiments. The performances of the participants were closely observed and their performances using white cane and NavGuide were compared.

The first experiment was performed by each participant two times, first with white cane and then with NavGuide. While using the white cane, participants constantly moved the white cane touching its tip on the surrounding surfaces to perceive the obstacles. On the contrary, NavGuide regularly provided proactive alerts of the obstacles to the participant, thus enabling the participant to identify the obstacle from a safe distance reducing the rate of collision compared to white cane as shown in Table V. Fig. 5 shows average completion speed of experiment by the participants in seconds. The participants completed the task faster with NavGuide as compared to white cane.

In the second experiment, the participants walked on a 3000 cm long road coming across 30 obstacles. Evaluation was done on white cane and NavGuide. The participants also faced pedestrian traffic while crossing the road. On an average, each participant faced 2.3 pedestrians in their path. The participants looked more comfortable wearing NavGuide as compared to white cane. The collisions while using white cane were higher as compared to collisions while wearing NavGuide as described in Table VI. Fig. 6 shows average completion speed of the outdoor experiment by the participants in seconds. The completion time with NavGuide was less as compared to the completion time while using white cane.

In the third experiment, the participants walked a "U"-shaped corridor and climbed an ascending staircase. Participants were comfortable tackling the obstacles in the path of the corridor with both white cane and NavGuide even though the comparative results of obstacle avoidance were better for NavGuide as described in Table VII. The main challenge observed was detecting and climbing the staircase. While using white cane, participants touched the tip of the white cane to detect the obstacles, often wrongly detecting the staircase as an obstacle and colliding with it. On the contrary, NavGuide provided alert to the

TABLE VII
AVERAGE NUMBER OF OBSTACLES COLLIDED (MAXIMUM 50 OBSTACLES: 25 FLOOR-LEVEL, 25 KNEE-LEVEL) IN THE "U"-SHAPED CORRIDOR

Blindness Type	Gender	White Cane			NavGuide		
		Floor level	Knee level	Total	Floor level	Knee level	Total
Total Blind	Male	5.29	3.23	8.52	3.53	1.39	4.92
	Female	5.31	3.47	8.78	3.72	1.52	5.24
Low Vision	Male	3.17	2.31	5.48	1.79	1.21	3.00
	Female	2.52	1.73	4.25	1.39	1.63	3.02

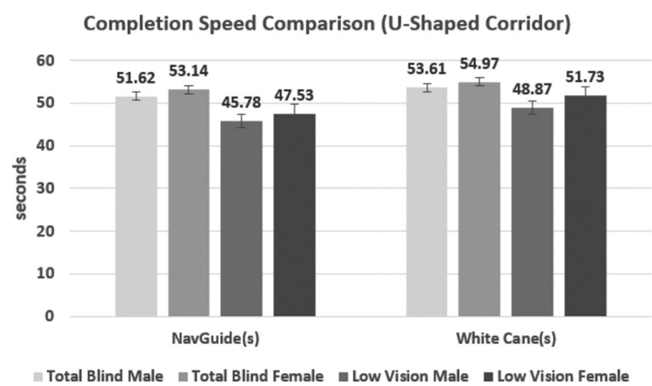

Fig. 7. Average completion speed of participants in the "U"-shaped corridor experiment.

TABLE VIII
AVERAGE NUMBER OF WET BLOCKS (MAXIMUM 30 WET BLOCKS) IN THE EXPERIMENT FOUR

Blindness Type	Gender	Wet Blocks
Total Blind	Male	24.73
	Female	27.13
Low Vision	Male	27.32
	Female	26.69

participant when he/she was approximately 150 cm away from the staircase using audio and tactile feedback thus enabling the user to avoid collision with the staircase. Fig. 7 shows average completion speeds of experiments by the participants in seconds. The experiment completion time was less with white cane compared to NavGuide but the obstacle collision was more.

In the fourth experiment, the participant walked in a room which was divided into 50 blocks wearing NavGuide, where water was spilled on the floor at 30 random blocks. The participants were awarded one point for correctly identifying a wet spot on the floor, on the basis of feedback provided by NavGuide. Table VIII describes the average score of participants.

Table IX provides details about the distribution of floor-level and knee-level obstacles in indoor, outdoor, and U-shaped corridor experiments.

A. Power Consumption Analysis

Table X provides details about current consumption of individual components in milli-Ampere (mA) of NavGuide.

TABLE IX
DISTRIBUTION OF OBSTACLES IN VARIOUS ENVIRONMENTS

Environment	Floor Level	Knee Level	Total
Indoor	5	5	10
Outdoor	15	15	30
U-Shaped Corridor	25	25	50

TABLE X
INDIVIDUAL COMPONENT CURRENT CONSUMPTION

Component	Current	Quantity	Total Current
Microcontroller	48	1	48
Vibration Motor	5	4	20
Ultrasonic Sensor	7	6	42
Audio Module	8	1	10
Liquid Detector	2	1	2

1) No-load condition
When the step down button is not pressed, all components of NavGuide except the microcontroller will be switched OFF, thus only the microcontroller will consume the current making the complete NavGuide system to consume only 48 mA of current.
2) Full-load condition
When the NavGuide has obstacles on all three sides (front, left, right) and is on a wet floor with the step down button pressed, all the components of NavGuide are activated, thus consuming maximum current of 120 mA.
3) Average-load condition
When the step down button is pressed, all the ultrasonic sensors (US) and wet floor detector (WD) modules get activated, thus current is consumed by the microcontroller, US, and WD. Further, when an obstacle is detected, the audio module and respective vibrator motors get activated consuming current.

B. NavGuide Working Time

The participants were provided with fully charged NavGuide. The participants used the NavGuide continuously until the power source was completely drained and the usage time was noted. Fig. 8 shows the NavGuide working time for 70 participants.

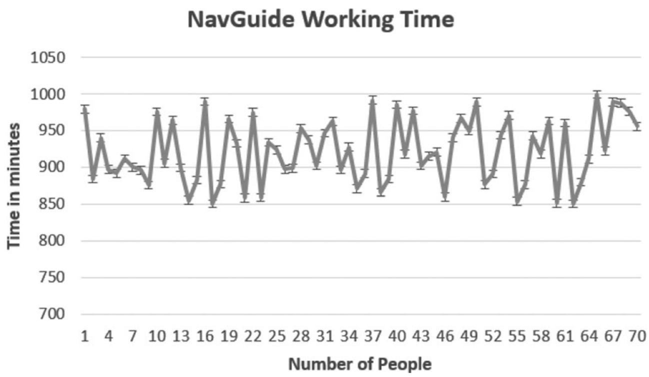

Fig. 8. Working time of NavGuide.

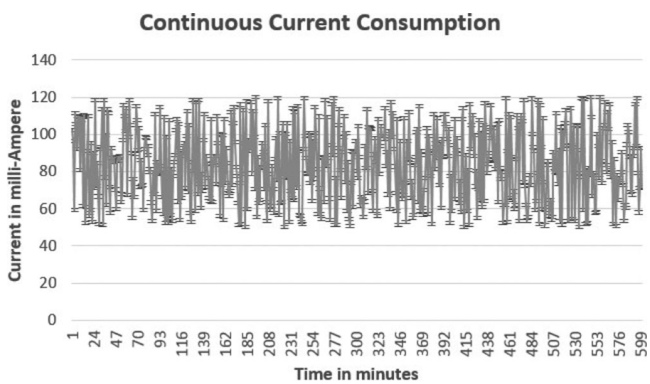

Fig. 9. Continuous power consumption details for NavGuide.

C. Continuous Power Consumption

NavGuide was used by one of our volunteers and was monitored for continuous current consumptions with changing surroundings for a period of 600 min. The data obtained is shown in Fig. 9.

VI. Statistical Analysis of the Performance of NavGuide

In this section, we use an inferential statistical method to compare the performances of NavGuide and white Cane. Let μ_N and μ_W denote the population mean number of collisions that a blind person has while using NavGuide and white cane respectively, and $\mu_d := \mu_W - \mu_N$. We test the following hypothesis

$$H_0 : \mu_d = 0$$

$$H_1 : \mu_d > 0.$$

For this purpose, we perform the paired t-test, using the statistic

$$t = \frac{\overline{d} - \mu_d}{s_{\overline{d}}} \tag{13}$$

since

1) the variance is unknown,
2) the samples are paired, and
3) our sample size is large ($n > 30$).

In (13), if n is the sample size, x_i^W and x_i^N, $i = 1, \ldots, n$ are the number of collisions of the ith blind person using white cane and NavGuide, respectively, then $\overline{d} := \frac{1}{n}\sum_{i=1}^{n} d_i$, $s_{\overline{d}} = \dfrac{S_d}{\sqrt{n}}$, $S_d := \sqrt{\frac{n(\sum_{i=1}^{n} d_i^2) - (\sum_{i=1}^{n} d_i)^2}{n(n-1)}}$ and $d_i = x_i^W - x_i^N$. Under the conditions above, t has a student t-distribution with $n-1$ degrees of freedom. For details, see [[24], ch. 10]. For the tests we perform below, the significance level will be $\alpha = 0.05$.

A. Performance in Controlled Indoor Experiment With 10 Obstacles

The following are the summary statistics obtained from the controlled indoor experiment
$n = 70$, $\sum_{i=1}^{n} d_i = 124$, $(\sum_{i=1}^{n} d_i)^2 = 15376$, $\sum_{i=1}^{n} d_i^2 = 300$, $S_d = 1.08$
$\overline{d} = 1.77$, $S_{\overline{d}} = 0.129$, $t = 13.73$, $df = 69$, $t_{\frac{\alpha}{2},69} = 1.995$.
Since $t > t_{\frac{\alpha}{2},69}$, i.e., the value of the statistic lies in the rejection region, we reject the null hypothesis. This shows that statistically, NavGuide has a better performance than white cane for indoor use.

B. Performance in Controlled Outdoor Experiment With 30 Obstacles

The summary statistics for the controlled outdoor experiment are as follows:
$n = 70$, $\sum_{i=1}^{n} d_i = 168$, $(\sum_{i=1}^{n} d_i)^2 = 28224$, $\sum_{i=1}^{n} d_i^2 = 828$, $S_d = 2.48$
$\overline{d} = 2.4$, $S_{\overline{d}} = 0.297$, $t = 8.093$, $df = 69$, $t_{\frac{\alpha}{2},69} = 1.995$.
Since $t > t_{\frac{\alpha}{2},69}$, i.e., the value of the statistic lies in the rejection region, we reject the null hypothesis. This shows that statistically, NavGuide has a better performance than white cane for outdoor use.

C. Performance for Experiment in U-Shaped Corridor With 50 Obstacles

Finally, for the U-shaped corridor with 50 Obstacles, we obtained the following summary statistics: $n = 70$, $\sum_{i=1}^{n} d_i = 190$, $(\sum_{i=1}^{n} d_i)^2 = 36100$, $\sum_{i=1}^{n} d_i^2 = 874$, $S_d = 2.279$
$\overline{d} = 2.71$, $S_{\overline{d}} = 0.272$, $t = 9.968$, $df = 69$, $t_{\frac{\alpha}{2},69} = 1.995$.
Since $t > t_{\frac{\alpha}{2},69}$, i.e. the value of the statistic lies in the rejection region, we reject the null hypothesis. This shows that statistically, NavGuide has a better performance than white cane for U-shaped corridor use.

VII. Discussion

The NavGuide detects ascending staircase, floor-level, knee-level obstacles in the surrounding using six ultrasonic sensors placed on the NavGuide shoes. We are aware that our current implementation of the NavGuide may have three limitations. The first is that it is unable to sense a pit or downhill. The second is that it is unable to sense downstairs. These limitations highlight the difficulty of constructing the logical map of the surrounding. However, a downhill can be detected using additional ultrasonic sensors facing towards the ground in the soles to give feedback on the distance. The third limitation of the NavGuide is that it senses a wet-floor only after a user steps on it. Therefore, it is not able to avoid accidents that are likely to occur at the interface of dry ground and wet ground due to a slipper floor. However, the wet-floor detection system is useful to provide feedback to the user about the wet floor, so that the user steps in a way that deliberately avoids potential problems or dangers of slipping on a wet floor.

The NavGuide provides feedback to the user using a wired or wireless headphone. In case a wireless headphone is used by the user an electromagnetic interference generated by an external source can potentially affect the feedback provided by the system to the consumer.

VIII. Conclusion and Future Work

This paper presented a novel solution, NavGuide, for visually impaired people. The NavGuide provides solutions to four fundamental shortcomings of the exiting ETAs.

1) It detects wet floors to avoid slipping accidents.
2) It detects floor-level and knee-level obstacles.
3) It provides simplified and prioritized information to a user's tactile and auditory senses.
4) It is cheaper and lightweight.

Due to these advantages the NavGuide is easy to use. Evaluation of the NavGuide with visually impaired people shows the effectiveness and usefulness irrespective of the number of years of blindness.

In future, the proposed system can be modified using artificial intelligence techniques that would forecast the human health condition and generate alerts. The next version of NavGuide can use commercially available RFID readers and passive ultra high frequency RFID tags to detect human object interactions in the form of motion and touch. Moreover, RFID readers and tags can also be use to identify objects.

References

[1] A. Aladrn, G. Lpez-Nicols, L. Puig, and J. J. Guerrero, "Navigation assistance for the visually impaired using RGB-D sensor with range expansion," *IEEE Syst. J.*, vol. 10, no. 3, pp. 922–932, Sep. 2016.

[2] T. Amemiya and H. Sugiyama, "Orienting kinesthetically: A haptic handheld wayfinder for people with visual impairments," *ACM Trans. Accessible Comput.*, vol. 3, no. 2, 2010.

[3] B. And, S. Baglio, V. Marletta, and A. Valastro, "A haptic solution to assist visually impaired in mobility tasks," *IEEE Trans. Human-Mach. Syst.*, vol. 45, no. 5, pp. 641–646, Oct. 2015.

[4] S. Bhatlawande, M. Mahadevappa, J. Mukherjee, M. Biswas, D. Das, and S. Gupta, "Design, development, and clinical evaluation of the electronic mobility cane for vision rehabilitation," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 22, no. 6, pp. 1148–1159, 2014.

[5] B. B. Blasch, R. G. Long, and N. Griffin-Shirley, "National evaluation of electronic travel aids for blind and visually impaired individuals: Implications for design," in *Proc. RESNA 12th Annu. Conf.*, 1989, pp. 133–134.

[6] N. Bourbakis, S. K. Makrogiannis, and D. Dakopoulos, "A system-prototype representing 3D space via alternative-sensing for visually impaired navigation," *IEEE Sensors J.*, vol. 13, no. 7, pp. 2535–2547, Jul. 2013.

[7] M. Bousbia-Salah, M. Bettayeb, and A. Larbi, "A navigation aid for blind people," *J. Intell. Robot. Syst.*, vol. 64, no. 3/4, pp. 387–400, 2011.

[8] J. A. Brabyn, "New developments in mobility and orientation aids for the blind," *IEEE Trans. Biomed. Eng.*, vol. 29, no. 4, pp. 285–289, 1982.

[9] G. Cheng, P. Zhou, and J. Han, "Learning rotation-invariant convolutional neural networks for object detection in VHR optical remote sensing images," *IEEE Trans. Geosci. Remote Sensing*, vol. 54, no. 12, pp. 7405–7415, Dec. 2016.

[10] B. W. Cie, 2016. [Online]. Available: http://bestpluton.free.fr/EnglishMiniRadar.htm. Accessed on: Jan. 2016.

[11] I. C. Council. 2006 international residential code," 2006. [Online]. Available: http://www.qis-tx.com/documents/stair.installation.guide-lines.pdf. Accessed on: Mar. 2016.

[12] D. Dakopoulos and N. G. Bourbakis, "Wearable obstacle avoidance electronic travel aids for blind: A survey," *IEEE Trans. Syst., Man, Cybern., Part C:*, vol. 40, no. 1, pp. 25–35, Jan. 2010.

[13] G. eye, "Guiding eye for the blind: Guide dog school general information," 2016. [Online]. Available: https://www.guidingeyes.org/about-us/general-information/. Accessed on: Apr. 2016,

[14] G. facts, "Blindness and visual impairments: Global facts," 2015. [Online]. Available: http://www.vision2020.org. Accessed on: Dec. 2015.

[15] National Federation of the Blind, "Blindness statistics: Statistical facts about blindness in the united states," Nat. Fed. Blind, Baltimore, MD, USA. 2014. [Online]. Available: https://nfb.org/blindness-statistics, Accessed on: Apr. 2016.

[16] A. GDP Research, 2016. [Online]. Available: http://www.gdp-research.com.au. Accessed on: Mar. 2016.

[17] M. A. Hersh and M. A. Johnson, *Assistive Technology for Visually Impaired and Blind People*. New York, NY, USA: Springer, 2008.

[18] T. Ifukube, T. Sasaki, and C. Peng, "A blind mobility aid modeled after echolocation of bats," *IEEE Trans. Biomed. Eng.*, vol. 38, no. 5, pp. 461–465, May 1991.

[19] K. Ito, M. Okamoto, J. Akita, T. Ono, I. Gyobu, and T. Takagi, "CyARM: An alternative aid device for blind persons," in *Proc. Conf. Human Factors Comput. Sci.*, 2005, pp. 1483–1486.

[20] M. C. Kang, S. H. Chae, J. Y. Sun, J. W. Yoo, and S. J. Ko, "A novel obstacle detection method based on deformable grid for the visually impaired," *IEEE Trans. Consumer Electron.*, vol. 61, no. 3, pp. 376–383, Aug. 2015.

[21] L. Kay, "Electronic aids for blind persons: An interdisciplinary subject," *IEE Proc. A, Phys. Sci., Meas. Instrum., Manage. Edu.–Rev.*, vol. 131, no. 7, pp. 559–576, 1984.

[22] LaserCane, "Lasercane walking stick," 2016. [Online]. Available: http://www.attainability.co.uk/lasercane-walking-stick/. Accessed on: Jan. 2016.

[23] K. M. Lee, M. Li, and C. Y. Lin, "Magnetic tensor sensor and way-finding method based on geomagnetic field effects with applications for visually impaired users," *IEEE/ASME Trans. Mechatronics*, vol. 21, no. 6, pp. 2694–2704, Dec. 2016.

[24] P. S. Mann. *Introductory Statistics*. New York, NY, USA: Wiley, 2011.

[25] P. B. L. Meijer, "An experimental system for auditory image representations," *IEEE Trans. Biomed. Eng.*, vol. 39, no. 2, pp. 112–121, 1992.

[26] L. B. Neto *et al.*, "A kinect-based wearable face recognition system to aid visually impaired users," *IEEE Trans. Human-Mach. Syst.*, vol. 47, no. 1, pp. 52–64, Feb. 2017.

[27] U. Oh, S. Branham, L. Findlater, and S. K. Kane, "Audiobased feedback techniques for teaching touchscreen gestures," *ACM Trans. Accessible Comput.*, vol. 7, pp. 3, 2015.

[28] U. Oh and L. Findlater, "A performance comparison of onhand versus onphone nonvisual input by blind and sighted users," *ACM Trans. Accessible Comput.*, vol. 7, pp: 14:1–14:20, 2015.

[29] X. Qian and C. Ye, "3D object recognition by geometric context and Gaussian-mixture-model-based plane classification," in *Proc. 2014 IEEE Int. Conf. Robot. Autom.*, May 2014, pp. 3910–3915.

[30] G. Sainarayanan, R. Nagarajan, and S. Yaacob, "Fuzzy image processing scheme for autonomous navigation of human blind," *Appl.*, vol. 7, no. 1, pp. 257–264, 2007.

[31] S. Shoval, J. Borenstein, and Y. Koren, "The N avbelt—A computerized travel aid for the blind based on mobile robotics technology," *IEEE Trans. Biomed. Eng.*, vol. 45, no. 1376–1386, Nov. 1998.

[32] I. Ulrich and J. Borenstein, "The guidecane-applying mobile robot technologies to assist the visually impaired," *IEEE Trans. Syst., Man, Cybern. Part A*, vol. 31, no. 2, pp. 131–136, Mar. 2001.

[33] UltraCane. 2016. [Online], Available: http://www.ultracane.com/. Accessed on: Jan. 2016.

[34] J. Xiao, S. L. Joseph, X. Zhang, B. Li, X. Li, and J. Zhang, "An assistive navigation framework for the visually impaired," *IEEE Trans. Human-Mach. Syst.*, vol. 45, no. 5, pp. 635–640, Oct. 2015.

[35] C. Yan *et al.*, "A highly parallel framework for HEVC coding unit partitioning tree decision on many-core processors," *IEEE Signal Process. Lett.*, vol. 21, no. 5, pp. 573–576, May 2014.
[36] C. Yan *et al.*, "Efficient parallel framework for HEVC motion estimation on many-core processors," *IEEE Trans. Circuits Syst. Video Technol.*, vol. 24, no. 12, pp. 2077–2089, Dec. 2014.
[37] X. Yang, S. Yuan, and Y. Tian, "Assistive clothing pattern recognition for visually impaired people," *IEEE Trans. Human-Mach. Syst.*, vol. 44, no. 2, pp. 234–243, Apr. 2014.
[38] C. Ye, S. Hong, X. Qian, and W. Wu, "Co-robotic cane: A new robotic navigation aid for the visually impaired," *IEEE Syst., Man, Cybern. Mag.*, vol. 2, no. 2, pp. 33–42, Apr. 2016.
[39] D. Zhang, J. Han, J. L, Y. S, and C. X, "Revealing event saliency in unconstrained video collection," *IEEE Trans. Image Process.*, vol. 26, no. 4, pp. 1746–1758, Apr. 2017.
[40] D. Zhang, J. Han, C. Li, J. Wang, and X. Li, "Detection of co-salient objects by looking deep and wide," *Int. J. Comput. Vis.*, vol. 120, no. 22, pp. 215–232, 2016.
[41] P. A. Zientara *et al.*, "Third eye: A shopping assistant for the visually impaired," *Computer*, vol. 50, no. 2, pp. 16–24, Feb. 2017.

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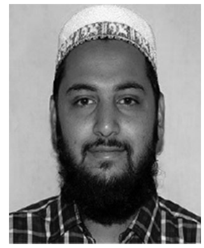

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